Symmetry breaking as a general design principle of oscillation-based methods for fixation and manipulation of nano-objects

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We present various examples of man-made and biological nanoscale actuators based on oscillations. In most cases it is the interplay of oscillation and friction which produces the driving effect. The basic idea of all such actuators is the same: an asymmetry in the oscillation causes a net directed motion. Introducing asymmetry in different components of the system (internal force, substrate, form of periodic actuation, etc.) leads to different types of drives. This symmetry concept is used to categorize and discuss the basic principles of nanoscale actuation and for formulating general principles of design guidelines that can be used to develop new concepts of nanoscale actuators.

Taking into account the general principle of symmetry breaking, a new concept for a high precision actuator suggested recently by the authors is discussed and its practical realization is outlined. This novel drive type consists of a sphere that is rolling back- and forth while being pushed on a movable substrate. The sphere acts as the drive and the substrate acts as the runner. A varying normal force leads to varying indentation depth and contact area during rolling. Together with the inertia of the runner, this asymmetry enables accurate control of the runner displacement. In theory, the actuator works with less wear because slip is completely omitted.

Keywords: biological motor systems, nanoscale actuators, stick-slip actuators, friction inertial actuators, oscillating rolling, nanotechnology, nanoscale propulsion

1. Introduction

The demand for precise manipulation, fixation and displacement devices increases with the ongoing miniaturization in science and technology. High-precision actuators are found for example in nanoscale data-storage [1], optical components [2] and *xy*-stages for micropositioning of probes [3]. Their efficiency and effectiveness highly depends on the dimensions since the major influences change with the scaling [4]. Basically, the logic of producing directed motion is scale-independent. Almost all types of macroscale actuators can also be realized on the nanoscale. Specifics for nanoscale are only the prevailing forces. For instance, many intercellular molecular motors operate in fluids. In this case, viscous effects become predominate on the nanoscale [5] as compared to inertial effects. Their ratio is characterized by the Reynolds number Re which is given as:

$$\mathrm{Re} = vL\rho/\eta. \qquad (1)$$

Here v is the velocity, L is the characteristic length of the device of the organism, η is the dynamic viscosity of the fluid and ρ denotes its density. For very small systems, the Reynolds number becomes very small and inertial forces can be neglected. Thus for any type of actuator based on hydrodynamic effects, the propulsion is predominantly due to viscous forces [6]. The deformations that generate the propulsion need to be cyclic and not symmetric with respect to the time inversion as purely symmetric movements do not lead to any net motion [7].

In systems that operate on solid substrates, contacts come into play. Nanoscale contacts are mainly influenced by adhesive forces. Bowling [8] categories these surface forces into three types:

(i) long range attractive forces as the electrostatic and magnetic forces;

(ii) interfacial interactions as capillary forces and other minor effects;

(iii) very-short range interactions as chemical and non-covalent bonds.

The long range attractive forces establish adhesion whereas the short interactions strengthen or weaken the connection. These various influences together with the ap-

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plied load and the contact area finally determine the nanoscale friction [9] and thus the capabilities of a particular nanoscale actuator.

In order to establish a certain categorization of nanoscale actuators, we would firstly like to identify the underlying basic principles. These may serve as a design basis for the development of new concepts in the field of nanoscale actuation and manipulation but also for the analysis and the improvement of existing ones. As a starting point, we consider a general model of a system used for manipulation or fixation, as sketched in Fig. 1. In the following such a system is simply referred to as an actuator.

No matter how the exact system looks like, it will consist of an object that is laying on some kind of substrate while being exposed to some excitation. The interplay of the three components generates or prevents motion of the relevant object. Despite the enormous number of different concepts of manipulation and fixation on the nanoscale, one can identify some major principles. First of all, producing a directed motion of an object requires some kind of asymmetry. This asymmetry can be realized in different forms. In the most obvious case the asymmetry occurs as an external force that acts in the desired direction. This actuation principle is referred to as "dragging". Furthermore, many manipulation systems used by, nature and man, rely on the transformation of oscillations into a directed motion. As a matter of fact this is one of the most universal principles. Basically, every oscillating system can be transformed into an "actuator" by introducing an asymmetry into the system. However, the asymmetry can occur in different forms resulting in different concepts of actuators: the case of an asymmetric substrate is referred to as the "ratchet and pawl principle"; asymmetry in the form of the excitation signal can be categorized as being from the "friction-inertia principle" (e.g. stick-slip drives); finally, a phase shift between the normal and tangential oscillations can be categorized as the "walking principle".

The paper is structured as follows. In chapter 2 we will explain the major concepts of actuation on the nanoscale and give examples. Using these principles as design guidelines, we introduce and discuss a new type of actuator in chapter 3. Finally, a conclusion is given in chapter 4.

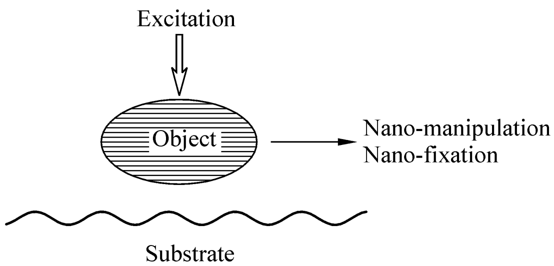

Fig. 1. Main components of a general actuator. Interaction of excitation, object and substrate induces directed motion.

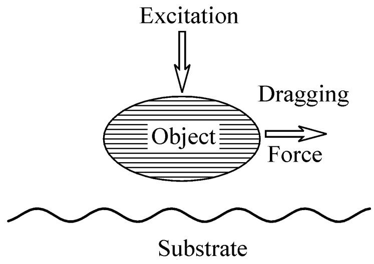

Fig. 2. Dragging principle. A force pulls the object in the desired direction.

2. Manipulation and fixation on the nanoscale

Depending on the scale, operating medium, environmental conditions, available energy sources and possibilities of control as well as geometrical and material parameters of a particular system, countless mechanicsms and principles of actuation have been proposed or have developed during the evolution [4].

2.1. Actuation and fixation on solids

Main requirement for any actuation is asymmetry in one of the main components of the general system sketched in Fig 1. In the following we describe the basic possibilities to introduce asymmetry into an oscillating system with the purpose to turn it into an actuator.

2.1.1. Dragging

The most obvious principle of manipulation is dragging. This characterizes the case in which the asymmetry is a force that acts on the object and pulls the object in the desired direction, as sketched in Fig. 2. Examples of nanoscale dragging are the scanning force microscope (SFM) [10] or atomic force microscope (AFM) [11]. As shown in Fig. 3, the AFM basically consists of a sharp tip that is dragged over a sample surface. Usually, using reflection of a laser beam, the AFM measures the vertical and lateral deflections of the cantilever. In turn the deflections give the force between the tip and the sample surface.

Besides many analytical applications, as for instance the determination of the roughness and the hardness of the sample surface, AFM can also be used to position single

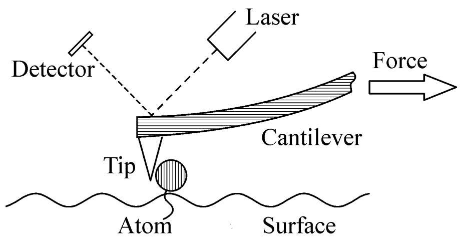

Fig. 3. Atomic force microscope (AFM) consisting of a tip that is dragged over a surface. The deflection of the cantilever gives the force between tip and surface. The AFM can also be used to position single atoms.

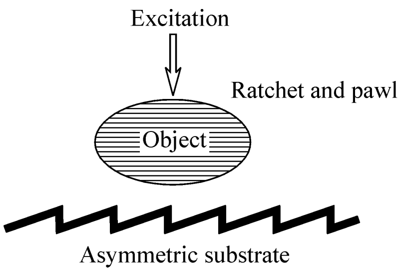

Fig. 4. Ratchet and pawl principle. The substrate is asymmetric. Together with form change of the transport mechanism this induces directed and irreversible motion.

atoms or molecules [12] that remain bounded to the surface. The AFM can therefore be used as an actuator. However, its working principle is based on dragging and requires some kind of macroscopic external excitation. An actuator that is based on dragging therefore can't be used in autonomous nanoscale systems.

2.1.2. Ratchet and pawl

The other large group of principles is based on the combination of oscillation and asymmetry. One important concept is the ratchet and pawl principle. In this case the asymmetry affects the substrate as shown in Fig. 4. A nanoscale system can use chemical or thermal energy to change its shape. If placed on an asymmetric substrate this form change can induce a stepwise motion. Due to the ratchet and pawl principle, the direction of the motion is fixed and irreversible [13].

One example for nanoscale transport using the ratchet and pawl principle is kinesin which is a two-headed, ATP-driven motor protein [14, 15]. Kinesin transports cellular cargo along microtubules which are part of the cytoskeleton that is found in the cytoplasm of cells. The microtubules have an intrinsic polarity with so-called plus and minus ends. The kinesin proteins read this polarity and move towards the ends. The directionality of the kinesin proteins is fixed. Some types move towards the rapidly growing plus ends, whereas other types move to the more static minus ends. Because of the asymmetry of the substrate, i.e. the microtubules, the motility of kinesin resembles to the ratcheting principle. In addition, kinesin rarely takes backwards steps even under a moderate backward load force. Therefore it is close to a perfect ratchet [16]. However, it is possible to reverse the directionality using protein engineering [17]. The stepwise motion of kinesin is induced by an alternating advance of the heads in sequence and a forceful interaction of the heads with the microtubule as shown in Fig. 5. However, the molecular details of this cyclic, mechanical ratcheting action remain obscure [16]. One plausible model for the transport is the hand-over-hand mechanism in which the kinesin heads step past one another, alternating the lead position [18]. Using interferometry technique and kinesin dimer that was attached to a bead showed that each step was 8 nm long, exactly the distance between successive kinesin bindings sited on the microtubule track [19].

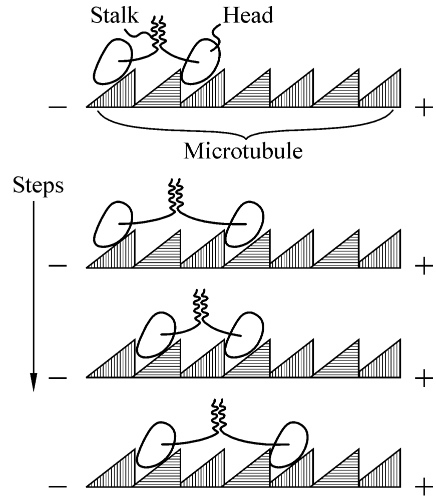

Fig. 5. Alternating advance model of kinesin motility. Front head moves forward while the rear head stays bound to the microtubule and so on.

The ratcheting principle is also used in the process of muscle contraction. Skeletal muscles are collections of rod-like cells called myofibril, each of which has the ability to contract. The myofibril is in turn composed of repeating sections of sarcomeres. This highly structured element essentially consists of sub-elements with an inner filament (myosin) and six outer filaments (actin) [20]. Small heads on the inner filament bind to the outer filaments. Through a biochemical process, the heads rotate towards the so called *z*-line, as depicted in Fig. 6.

Together with a synchronized loosening of the heads this effect contracts the sarcomere. Doing contraction, a single myosin head produces a force of 0.1–1.0 pN and its rotation leads to a relative displacement of 5.3 nm [20]. Human muscles consist of up to 100 millions of sarcom-

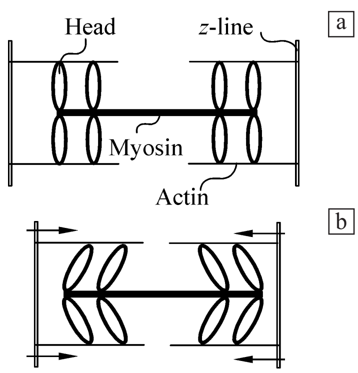

Fig. 6. Schematic of a sarcomere: (a) relaxed state, (b) rotation of the head leads to contraction of the sarcomere.

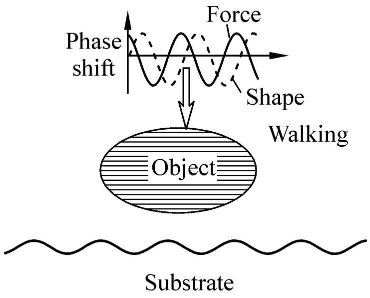

Fig. 7. Walking principle. A phase shift of the normal and tangential contact forces *N* and *T* induces a directed motion even for a symmetric substrate.

eres to generate a significant macroscopic force. One important experimental result is the hyperbolic dependency of the force of a muscle *F* on the contraction velocity *v* [21]:

$$F = F_0 \frac{1 - v/v_0}{1 + v/(v_0 k)}. \tag{2}$$

Here v_0 denotes the maximal sliding velocity and F_0 the maximal isometric load of the muscle. The parameter *k* is in the range of 0.15–0.25. Equation (2) illustrates the well-known everyday phenomenon that the heavier the weight, the slower the velocity with which it can be lifted.

2.1.3. Walking

However, an asymmetry of the substrate is not a necessity and not always wanted prerequisite of a directed motion. Directed movement can also be induced on a symmetric substrate by introducing an asymmetry in the oscillation. One of the possibilities is to induce superimposed normal and tangential oscillations with a phase shift between them. This principle can be generally classified as "walking" (or "jumping" in the case of only one foot), as depicted in Fig. 7. As in the walking of human beings, the forward movement occurs in the state of small (or absent) normal force, while the back movement occurs in the state of high normal force.

The "walking" principle can be realized with any number of "legs"—one (jumping), many (caterpillars, millipedes) or infinite (traveling wave motors) [22]. Instead of a phase shift between normal and tangential oscillations, a phase shift between the movements of different parts of the system can be used. One example for this is the "three-body-machine" shown in Fig. 8 [23, 24]. It consists of three linked bodies that are connected via springs.

The lengths of the springs l_1 and l_2 are controllable. Together with the periodic potential, the oscillations of the springs change the contact forces. In combination with the form change this can lead to a directional movement of the system for which the movement direction as well as the speed are arbitrary controllable. The system models an object of atomic size that experiences the action of a periodic

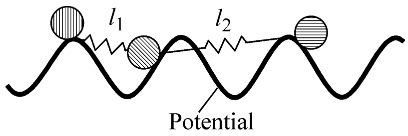

Fig. 8. Three-body machine in a periodic potential. The lengths of the springs l_1 and l_2 are oscillating what together with the periodic potential generates a directed motion of the system using the walking principle.

crystalline potential, i.e. the system is laying on a crystalline surface. In doing so, it shows that the minimum size of a nanoscale system using the walking principle solely depends on the possibility of practical realization of the two periodic actions, i.e. the oscillations of l_1 and l_2. The induced motion can occur in a certain direction even in the absence of a macroscopic force or in the presence of a counter force, i.e. the system can be used to transport objects.

2.1.4. Friction-inertia-principle

Many technical applications are characterized by a simultaneous demand for accurate resolution in the range of nanometers and for long stroke in the range of millimeters. One widespread solution for this problem is the friction-inertia principle, which is based on an asymmetric (in time) excitation signal. The basic principle is sketched in Fig. 9.

A technical realization is the stick-slip drive [25, 26] as shown in Fig. 10. The oscillating drive is pressed on the runner. The characteristic back and forth motion of the drive x_d is such that it moves slowly to the right and much faster to the left. Together with the stick-slip effect [27] in the contact between drive and runner this generates an asymmetric force path of the driving force. In combination with the inertia of the runner a well to control motion is generated. Typically, a high-resolution piezoelectric motor is used to drive the runner [25, 26].

With respect to friction and adhesion, there are two important differences between technical and biological nanoscale systems. In technical systems, the tribological prop-

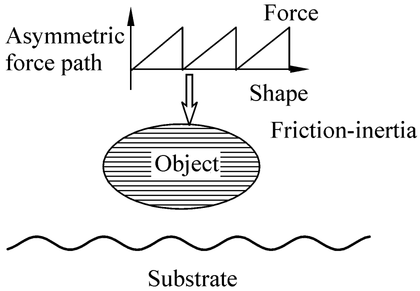

Fig. 9. Friction-inertia principle (stick-slip-drive). Asymmetric force path together with the inertia induces directed motion of the moving object.

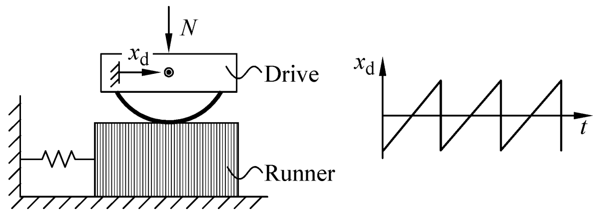

Fig. 10. Stick-slip drive using the friction-inertia principle. The motion of the drive x_d follows a saw tooth. This induces an asymmetric forth path and a directed motion of the runner

erties are mainly determined by the state of the top-most atomic layer of the solid, whereas in biological systems the influence of the bulk is strong. Second, biological systems almost always use lubrication, while no reliable technical concept for lubrication on the nanoscale does exist [28]. For example, the application of a liquid to a nanoscale actuator would prevent operation due to capillary forces. Yet without lubrication technical nanoscale systems are prone to high-friction and wear [28]. This provides a special challenge in the technical realization of actuators [29]. The working principle of stick-slip actuators (SSA) is therefore accompanied by a steady wear that decreases the controllability and can lead to failure of the drive [30].

2.1.5. Oscillation tweezers

Even if both, the substrate and the excitation signal, are symmetric, asymmetry can still be induced by introducing a gradient of the oscillation amplitude. We will denote this group of drives as "oscillation tweezers" in analogy to "optical tweezers" which can be considered as a representative of this group. This kind of actuation is based on a general principle of interaction of macroscopic motion and rapid oscillations. One of the known methods to couple the macroscopic motion and oscillations was proposed by P.L. Kapitza [31–33] and is described in detail in [34]. Kapitza showed that if a "particle" is placed in a rapidly oscillating field, whose amplitude depends on the macroscopic coordinate x, then the motion of the particle averaged over the oscillations is the same as if the particle was moving in the effective potential U_{eff} given by:

$$U_{\text{eff}}(x) = U(x) + K_{\|}(x). \qquad (3)$$

Here $U(x)$ is the macroscopic potential energy and $K_{\|}(x)$ is the part of kinetic energy due to the rapid oscillations in the direction of the generalized coordinate x. One can show that if the rapidly oscillating field causes oscillations perpendicular to the generalized coordinate x with the kinetic energy $K_{\perp}(x)$, then (3) has to be replaced by:

$$U_{\text{eff}}(x) = U(x) + K_{\|}(x) - K_{\perp}(x). \qquad (4)$$

The additional "parallel" and "perpendicular" contributions to the kinetic energy can be produced by external mechanical forces as in the problem of fixing the equilibrium of the inverted pendulum [34], or by electrical or magnetic fields (inclusive optical fields). Equation (4) states that the particles will move in the direction of the maxima or minima of the electrical field intensity (depending on the relative direction of the field and the macroscopic motion of the object). A schematic sketch of such oscillation tweezers is given in Fig. 11.

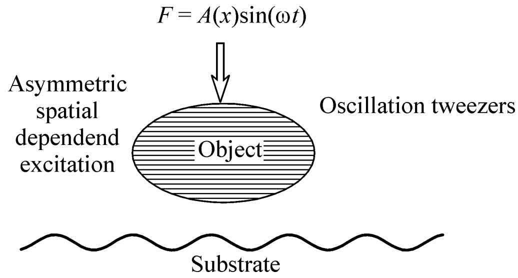

Fig. 11. Oscillation tweezers principle. Asymmetric spatial dependence of the oscillation amplitude of the excitation generates motion towards or away from the maximum amplitude.

Examples of such a fixation technique based on the influence of oscillations are the so called optical tweezers. Its widespread applications range from optical trapping and cooling of single atoms to the trapping and manipulation of living cells and organic molecules and the measurement of mechanical forces and elastic properties of cells and molecules [35, 36]. Optical tweezers use tightly focused laser beams that generate radiation pressure on dielectric particles [37]. In the focus of the beam, the dielectric particles experience a force called the gradient force that is directed towards the laser focus where the light intensity is highest. This force arises from the momentum imparted to the particle as it scatters the laser light.

The purely macroscopic view described by (4) is valid as long as we deal with particles whose size is much smaller than the wavelength of light. Otherwise, if the diameter of a

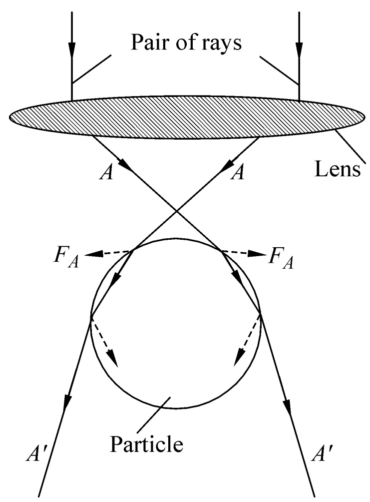

Fig. 12. Schematic of ray optics of spherical particle trapped by the laser light of a single-beam gradient force trap [38].

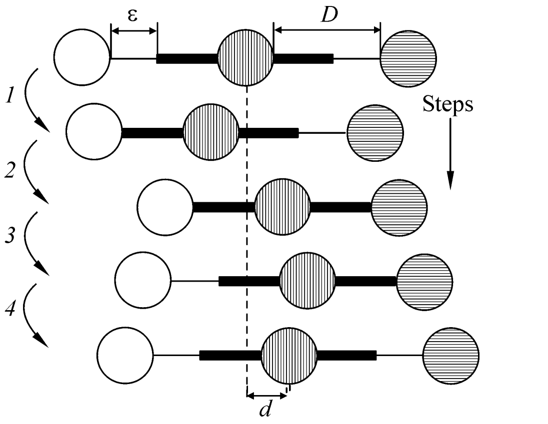

Fig. 13. 4-stage cycle motion of the three linked spheres-swimmer [39]. Non- time-reversible motion leads to propulsion of the system with translation *d*.

particle is large compared with the wavelength of laser light, ray optics can be used to describe the scattering and optical momentum transfer to the particle [38]. Figure 12 shows the scattering of a pair of laser rays *A* by a lossless dielectric sphere. Refraction changes the direction of the emergent rays *A′* that generates momentum transfer from the incident light to the particle. The resulting forces F_A on the particle lead to a substantial net backward trapping force component towards the beam focus above the sphere. Optical trapping was used for particle sizes ranging from a few nm to a hundreds of μm and cooling of atoms was achieved from temperatures ~10^3 K down to ~10^{-6} K [35].

2.2. Nanoscale propulsion in liquids

Propulsion in liquids also requires symmetry breaking. One theoretical example that enables propulsion at low Reynolds number is given by Najafi and Golestanian [39]. Their swimmer consists of three spheres with radius *R* that are linked by extendible rods with initial length *D* as shown in Fig. 13. The spheres are assumed to swim in highly viscous fluid. Extension and contraction of the rods leads to a nonreciprocal relative motion of the spheres. Fig. 13 depicts one complete cycle of motion. The elongation of the rods per step is denoted ε and takes place with a relative velocity *W*. Only one rod is elongated or shortened per step. As can be seen from Fig. 13, the 4-stage cycle is not time-reversible. The internal relative motion is of the general form of a traveling wave, which is the simplest nonreciprocal motion.

The characteristic motion produces a net translation of the system *d* in each cycle. For small internal deformations ε/D the average swimming velocity v_s is given as [39]:

$$v_s = 0.7W(R/D)(\varepsilon/D)^2. \quad (5)$$

Thus, the velocity depends on the internal velocity *W* and is a quadratic effect of the internal deformation.

The same kind of asymmetry can be produced in a multi-body-system by sending a traveling wave along a molecule-chain or—even simpler—by rotating a helix which automatically produces a wave traveling in a definite direction depending on the rotation direction. Microorganisms such as bacteria or some eukaryotic cells use a variety of movable hair-like structures for propulsion, known as flagella [40]. The asymmetry in this case is found in the rotating element. Unicellular organisms like protozoa or bronchial cells use flagella that resemble an elastic rod. Internal stresses lead to a wave-like bending of the rod that generates propulsion or transport. In contrast, some bacteria like e. coli exhibit helically shaped flagella that are driven by a rotary motor as depicted in Fig. 14a. The flagellar motor was the first biological rotary device discovered [41] and the molecular processes involved are still not fully understood.

Its driving principle is based on ion flow across the cytoplasmic membrane driven by an electrochemical gradient and enables rotational frequencies up to several hundred Hz

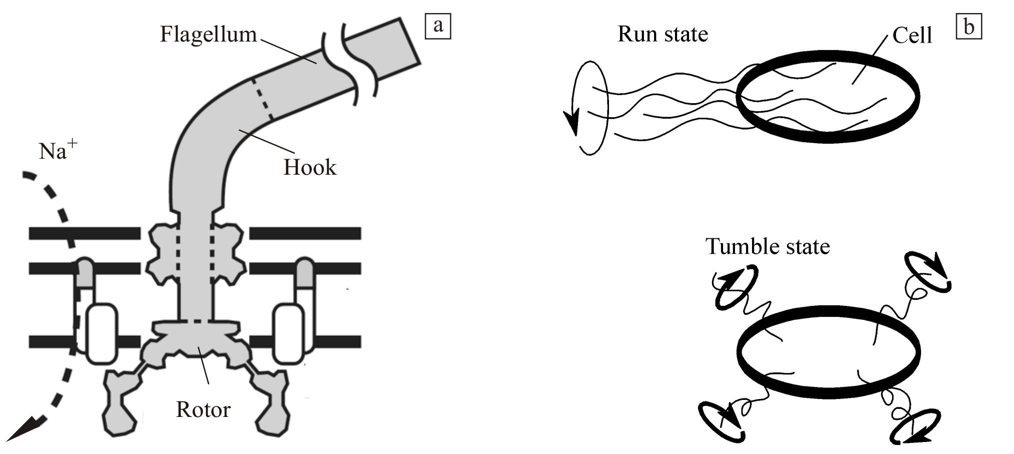

Fig. 14. (a) Schematic of Na^+ driven flagellar motor with rotor and connection hook between motor and flagellum [42]. (b) Run-state with counter clockwise rotation and tumble-state with clockwise rotation of the flagellum.

[42]. The rotation leads to a corkscrew like motion of the helical filaments (flagella) that generates the propulsion and a velocity of the cell up to 10–20 μm/s. There are two states of motion as depicted in Fig. 14b. In case of a counter-clockwise rotation, the flagella lay around the cell and form a common set that can act coordinated: The cell is in the "run" state and swims steadily in a direction roughly parallel to its long axis. A clockwise rotation causes the bundle to fly apart: The cell then moves erratically in place and is in the "tumble" state [43].

2.3. Basic principles

Finally, we can summarize the basic principles used for fixation and manipulation on the nanoscale using oscillations:

(i) ratchet and pawl: asymmetric substrate;

(ii) walking: phase shift between normal and tangential oscillations of shape and contact forces;

(iii) friction-inertia: asymmetric oscillations of the excitation;

(iv) oscillation tweezers: asymmetric spatial dependence of the oscillation amplitude;

(v) traveling wave (or rotation of a helix).

All of these principles rely on introducing asymmetry in one of the components of the actuator. However, the different principles act on different components of the system as depicted in Fig. 15.

The principles serve as general design guidelines for the development of new concepts of actuation on the nanoscale. Depending on in which of the different components it is easiest to induce an asymmetric oscillation, the corresponding principle can be used as a starting point.

3. The oscillating rolling drive

In the following, we use the concept of symmetry breaking as a general design principle and describe a promising new approach for a low-wear actuator recently proposed in [44] This so called oscillating rolling drive (ORD) combines the friction-inertia effect with the principle of oscillating rolling. For convenience of the reader we repeat some part of derivations from [44]. The suggested principle allows to generate a well-to-control high-precision motion. In this case slip effects and the associated wear can theoretically be completely omitted. This is a crucial advantage compared to actuators that are based on the combination of friction-inertia and stick-slip effects.

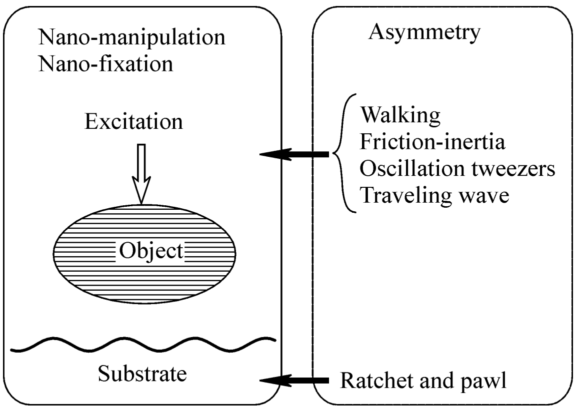

Fig. 15. Main components of a generic actuator and different principles for manipulation and fixation of nanoscale objects using the concept of asymmetric oscillations.

As a starting point we consider a system consisting of a rigid sphere with radius R and a movable elastic substrate with effective modules E^* and G^* as depicted in Fig. 16. We assume dry friction of the Coulomb type with constant coefficient of friction μ between the contacting bodies. A description for this initial static tangential contact of a rigid sphere and an elastic half-space is given for example in the book of Popov [45]. The normal load N leads to the indentation depth d, which is defined as the vertical displacement of the sphere counted from the first contact with the runner. Both bodies only touch within a circular area that is delimited by the contact radius a.

The actuation is based on an oscillating rolling of the sphere with varying normal force. The sphere acts as the drive and the substrate acts as the runner. The process is divided into two steps. In the so called "forth-step", the center of the sphere moves with velocity v to the right and rotates clockwise with the angular velocity ω as shown in Fig. 17a. During the "back step", the sphere moves to the left with velocity $-v$ and rotates counter-clockwise with $-\omega$ as shown in Fig. 17b.

If the normal force remains constant over the oscillation period, then the total relative displacement of the plate and roller at the end of an oscillation period will be equal to zero because of the symmetry of the system. However, if the normal force is oscillating with some phase shift compared to the oscillating rolling (e.g. the normal force is larger during the "forth-step" and smaller during the "back-step") then there will be a net macroscopic movement, so that the system can be used as a "drive". The physical reason for this asymmetry can be explained most easily in the case of relatively large oscillation amplitude. In this case, the back and forth rolling can each be considered as stationary rolling. For a stationary runner, the creep ratio $s_{\text{stat}-1}$ will be

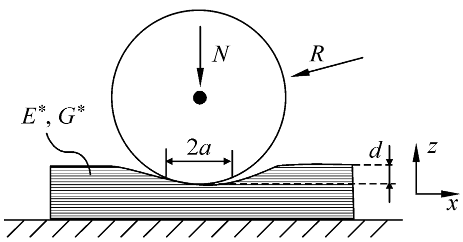

Fig. 16. Hertzian contact of rigid sphere with radius R and movable elastic substrate. Normal force N leads to indentation d and contact length $2a$.

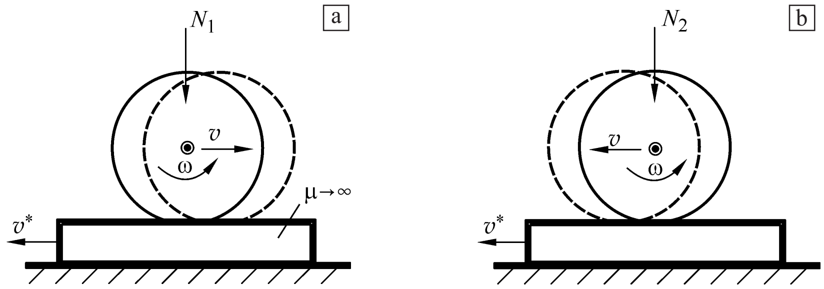

Fig. 17. Oscillating rolling drive: (a) forth step with force N_1, (b) back step with lower force $N_2 < N_1$.

positive $s_{\text{stat}-1} = (\omega R - v)/v > 0$. The corresponding creep ratio is equal to $s_{\text{stat}-2} = (-\omega R + v)/v < 0$. In case of a constant normal force, i.e. a symmetric actuation, the sum of both creep values is exactly zero, thus there is no net tangential movement. The superposition of the oscillating rolling and varying normal force introduce asymmetry into the system. The detailed analysis of the macroscopic behavior induced by this movement, is described in [44].

3.1. Outline of the experimental setting

The proposed concept resembles to the so called ratcheting effect, where a spatial variation of stick and slip zones in the contact interface leads to a continuing rigid body motion [46]. An experimental proof for the ratcheting effect is given in recent papers of the authors [46–48]. In this case, an oscillating rolling sphere together with a tangential load is used to generate motion. Using this as a starting point, a possible experimental setting of the proposed model, i.e. a proof of concept, can be as shown in Fig. 18. Here, a steel block acts as the runner and a ruby hemisphere acts as the drive. Two independently controlled piezoelectric actuators enable a rolling motion of the sphere that can be superposed by a changing normal deflection. This concept is similar to the oscillating hemispheres that are used in the Ramona nanoscale drive [49, 50]. A flexible bar acts as a shear force bearing for the piezoelectric actuators. This concept is the basis for the experimental realization of the drive in the next step.

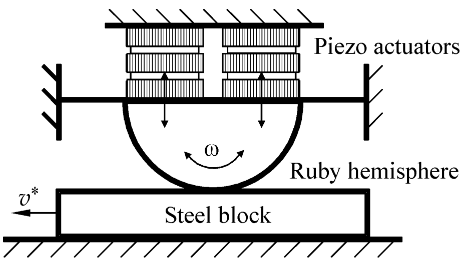

Fig. 18. Outline of the possible experimental setting based on the oscillating rolling experiments [48, 49] and the oscillating hemispheres of the Ramona nanoscale drive [50].

4. Summary

We presented various examples for biological and manmade actuators. We identified the general basic principles of manipulation and fixation based on oscillations. It shows that the underlying general idea of any kind of oscillation driven actuator is breaking the symmetry of the system. The categorization of the different principles can be used as a starting point for the development of new nanoscale actuators.

Following the concept of symmetry breaking, we discussed a new concept for a nanoscale actuator based on inertia effects and the principle of oscillating rolling and suggested it experimental realization. The suggested principle of symmetry breaking is scale invariant and can be used for designing or optimization of micro- and nanohandling devices.

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